Unparticle Induced Baryon Number Violating Nucleon Decays

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Abstract

We study baryon number violating nucleon decays induced by unparticle interactions with the standard model particles. We find that the lowest dimension operators which cause nucleon decays can arise at dimension $6+(d_s-3/2)$ with the unparticles being a spinor of dimension $d_s = d_{\mathcal{U}}+1/2$. For scalar and vector unparticles of dimension $d_{\mathcal{U}}$, the lowest order operatoers arise at $6+d_{\mathcal{U}}$ and $7+d_{\mathcal{U}}$ dimensions, respectively. Comparing the spinor unparticle induced $n \to O^s_{\mathcal{U}}$ and experimental bound on invisible decay of a neutron from KamLAND, we find that the scale for unparticle physics is required to be larger than 10^{10} GeV for $d_{\mathcal{U}} < 2$ if the couplings are set to be of order one. For scalar and vector unparticles, the dominant baryon number violating decay modes are $n \to \bar{\nu} + O_{\mathcal{U}}(O^\mu_{\mathcal{U}})$ and $p \to e^+ + O_{\mathcal{U}}(O^\mu_{\mathcal{U}})$. The same experimental bound puts the scales for scalar and vector unparticle to be larger than 10^7 and 10^5 GeV for $d_{\mathcal{U}} < 2$ with couplings set to be of order one. Data on $p \to e^+$invisible puts similar constraints on unparticle interactions.

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One of the outstanding problems of modern particle physics it whether proton is stable or not. If proton decays, baryon number is violated. Baryon number violation is one of the necessary conditions to explain why our universe at present is dominated by matter if initially there are equal amount of matter and anti-matter as shown by Sakharov[1]. It also provides a test for grand unified theories. Experimentally, no proton decay has been detected setting a lower bound of 10^{33} years[2] for proton lifetime. The Standard Model (SM) Lagrangian does not allow baryon number violating renormalizable interactions and therefore forbids proton or more generally baryon number violating nucleon decays. Although non-perturbative effects can induce baryon number violation in the SM, it is too small for any experimental observation. In grand unification theories, such as $SU(5)$ theory, baryon number can be violated and proton can decay by exchanging heavy particles. The long lifetime bound on proton pushes the scale of the heavy particle mass to the unification scale and rules out some grand unification models. If nonrenormalizable terms are allowed in the Lagrangian, it is possible to have baryon number violation in the SM. The lowest dimension operators of this kind have dimension six. When going beyond the SM, it is also possible to have renormalizable baryon number violating interactions at low energy, such as in R-parity violating supersymmetric theories. It is of interest to determine the constraints on the interaction strengthes of these operators. Such studies can provide information about the scale where the new physics effects become important. Much work has been done along this line. In this work we study possible effect of unparticle physics on baryon number violating nucleon decays.

The concept of unparticle [3] stems from the observation that certain high energy theory with a nontrivial infrared fixed-point at some scale $\Lambda_\mathcal{U}$ may develop a scale-invariant degree of freedom below the scale. The unparticle kinematics is mainly determined by its scaling dimension $d_\mathcal{U}$ under scale transformations. The unparticle must interact with particles, however feebly, to be physically relevant; and the interaction can be well described in effective field theory. At low energy the interaction of an unparticle $O_\mathcal{U}$ with an operator composed of SM particles O_{SM} of dimension d_{SM} can be parameterized in the form $\lambda\Lambda_\mathcal{U}^{4-d_{SM}-d_\mathcal{U}}O_{SM}O_\mathcal{U}$. There has been a burst of activities on unparticle studies[4, 5, 6, 7, 8, 9, 10, 11, 12, 13] since the seminal work of Georgi [3].

An unparticle looks like a non-integral $d_\mathcal{U}$ dimension invisible particle. Depending on the nature of the original operator inducing the unparticle and the mechanism of transmutation,

the resulting unparticles may have different Lorentz structures, such as scalar ($O_{\mathcal{U}}$), spinor ($O^s_{\mathcal{U}}$) and vector (O^μ_U) unparticles. We use $d_{\mathcal{U}}$ to indicate the dimensions of $O_{\mathcal{U}}$ and $O^\mu_{\mathcal{U}}$, and $d_s = d_{\mathcal{U}} + 1/2$ to indicate the dimension of $O^s_{\mathcal{U}}$. When taking the limit that $d_{\mathcal{U}} = 1$, the operators go to the limit of ordinary scalar, vector and spinor fields. There are many unknowns when writing down the effective interaction with unparticles even if one assumes that it is a SM singlet with known spin structure[6]. Most of the phenomenological studies then focused on constraining unparticle interactions with the SM particles using various processes. In our study of unparticle interaction induced baryon number violating nucleon decays we will also use the effective field theory approach. We first identify all possible low dimension operators relevant and then constrain the couplings.

In the SM, operators which can induce baryon number violating nucleon decays can only be generated at dimension six or higher. With unparticles, the lowest dimension operators can arise at $6 + (d_s - 3/2)$ with the unparticles being a spinor. For scalar and vector unparticles, the lowest order operatoers arise at $6 + d_{\mathcal{U}}$ and $7 + d_{\mathcal{U}}$ dimensions, respectively. We find that the recent result on invisible decay of a neutron from KamLAND[14] can put very stringent bounds on the relevant coupling. A reliable bound on proton decay into a positron and missing energy can also put stringent constraints. We now proceed with details.

Let us begin by listing the dimension six operators which violate baryon number in the SM,

$$
\begin{aligned}
&O_{QQQ} = \bar{Q}^c_L Q_L \bar{L}^c_L Q_L, \;\; O_{QQU} = \bar{Q}^c_L Q_L \bar{E}^c_R U_R, \;\; O_{DUQ} = \bar{D}^c_R U_R \bar{L}^c_L Q_L, \\
&O_{UUD} = \bar{U}^c_R U_R \bar{E}^c_R D_R, \;\; O_{DUU} = \bar{D}^c_R U_R \bar{E}^c_R U_R, \;\; O_{QQD} = \bar{Q}^c_L Q_L \bar{\nu}^c_R D_R, \\
&O_{DDU} = \bar{D}^c_R D_R \bar{\nu}^c_R U_R, \;\; O_{UDD} = \bar{U}^c_R D_R \bar{\nu}^c_R D_R. \qquad (1)
\end{aligned}
$$

Here we have also included operators involving right-handed neutrinos which may be needed for neutrino mass in the Standard Model. Each operator is associated with a coupling strength λ_i/Λ^2. Here Λ is the scale where the baryon number violation is generated due to new physics effects. With a given Λ, λ_i indicates the relative strength of each operator.

The lowest dimension operators which violate baryon number can be constructed involve spinor unparticles. They are given by

$$
O^s_{QQD} = \bar{Q}^c_L Q_L \bar{O}^s_{\mathcal{U}} D_R, \;\; O^s_{UUD} = \bar{U}^c_R U_R \bar{O}^s_{\mathcal{U}} D_R, \;\; O^s_{DUU} = \bar{D}^c_R U_R \bar{O}^s_{\mathcal{U}} U_R. \qquad (2)
$$

Each operator is associated with a coupling $\lambda^s_i/\Lambda^{d_{\mathcal{U}}+1/2}_{\mathcal{U}}$. These operators look similar to the

one with the spinor unparticle replaced by a right-handed singlet neutrino in form. However, there is a crucial difference that with unparticle, one can talk about a baryon decay into an unparticle, but not decay into another particle. We will come back to this later.

For scalar unparticles, in order to have baryon number violation, one has to go to at least dimension $6+d_{\mathcal{U}}$. The lowest dimension ones can be obtained by attaching a scalar unparticle $O_{\mathcal{U}}$ to the operators in eq.(1), such as $O^{\mathcal{U}}_{QQQ} = \bar{Q}^c_L Q_L \bar{L}^c_L Q_L O_{\mathcal{U}}$, with λ_i/Λ^2 replaced by $\lambda^{\mathcal{U}}_i/\Lambda^{d_{\mathcal{U}}+2}_{\mathcal{U}}$.

For vector unparticles, one has to go to even higher order, at least $7 + d_{\mathcal{U}}$. The lowest dimension ones can be obtained by attaching the unparticle to the operators in eq.(1) and inserting $O^{\mu}_{\mathcal{U}}$, derivative ∂^{μ} and the covariant derivative D_{μ} in between the bi-spinors in eq.(1) at appropriate places, for example $\bar{Q}^c_L Q_L \bar{L}^c_L \sigma_{\mu\nu} Q_L \partial^{\mu} O^{\nu}_{\mathcal{U}}$. The associated coupling should then be replaced by $\lambda^{\mu}_i/\Lambda^{d_{\mathcal{U}}+3}_{\mathcal{U}}$.

The above operators can induce baryon number violating nucleon decays. Upper bound on relevant decay modes can be used to put constraints on the corresponding parameters. Since the unparticle behaves like an invisible object which carries away energy and escape detection, the signature is missing energy, the invisible part of the decay. We now study the constraints on the couplings of the above mentioned operators.

The baryon number violating operators with a spinor unparticle will induce $n \to O^s_{\mathcal{U}}$ decay. The experimental signature is total invisible decay of a neutron. For this decay there is a strong recent bound from Kamland[14] with $\tau(n \to \text{invisible}) > 5.8 \times 10^{30}$ years. Using this bound we can put a very stringent bound on the couplings. Let us take the operator $\bar{Q}^c_L Q_L \bar{O}^s D_R$ to show details.

The matrix element for this decay is given by

$$M(n \to \mathcal{U}) = 2\frac{\lambda_{QQD}}{\Lambda^{d_{\mathcal{U}}+1/2}_{\mathcal{U}}}\alpha \bar{O}_s R n, \tag{3}$$

where the parameter α is defined by $\alpha R n = - < 0|(\bar{u}^c_{\beta} L d_{\gamma}) R d_{\alpha} \epsilon^{\alpha\beta\gamma}|n >$. Here $R(L) = (1 + (-)\gamma_5)/2$.

Several other related matrix elements will be used later. We summarize the definitions here. They are $\alpha L n =< 0|(\bar{u}^c_{\beta} R d_{\gamma}) L d_{\alpha} \epsilon^{\alpha\beta\gamma}|n >$, $\beta L n =< 0|(\bar{u}^c_{\beta} L d_{\gamma}) L d_{\alpha} \epsilon^{\alpha\beta\gamma}|n >$ and $\beta R n = - < 0|(\bar{u}^c_{\beta} R d_{\gamma}) R d_{\alpha} \epsilon^{\alpha\beta\gamma}|n >$. The absolute values of α and β are almost equal to each other. These matrix elements have been calculated on the lattice recently. Calculations in ref.[15] give $\alpha = -0.0118(21)$ GeV^3 and $\beta = 0.0118(21)$ GeV^3, and calculations in ref.[16] give

$|\alpha| = 0.0090(+5-19)$ GeV^3 and $|\beta| = 0.0096(09)(+6-20)$ GeV^3. In our later discussions we will use 0.01 GeV^3 for both $|\alpha|$ and $|\beta|$.

In calculating decay width, one should be careful with the phase space of a unparticle which is dramatically different than that for a particle. For a usual massless particle, the phase space is given by $2\pi\theta(p^0)\delta(p^2)d^4p/(2\pi)^4$, but for a unparticle it is replaced by $A_{d_\mathcal{U}}\theta(p^0)\theta(p^2)ad^4p/(2\pi)^4$. Here $A_{du} = (16\pi^{5/2}/(2\pi)^{2d_\mathcal{U}})\Gamma(d_\mathcal{U}+1/2)/(\Gamma(d_\mathcal{U}-1)\Gamma(2d_\mathcal{U})$. For scalar and vector unparticles, $a = (p^2)^{d_\mathcal{U}-2}$, and for spinor unparticle, $a = (p^2)^{d_s-5/2} = (p^2)^{d_\mathcal{U}-4}$.

Due to the unique phase structure of unparticles, a particle of any mass can decay into an unparticle. For $n \to O^s_\mathcal{U}$, we obtain

$$\Gamma(n \to O^s_\mathcal{U}) = 4A_{d_\mathcal{U}}|\lambda^s_{QQD}|^2\frac{|\alpha|^2}{m_n^5}\left(\frac{m_n}{\Lambda_\mathcal{U}}\right)^{2d_\mathcal{U}+2}. \quad (4)$$

Here we have used parity conserving spin-sum of spinor unparticle field[5], $\sum_{spin} O^s_\mathcal{U}\bar{O}^s_\mathcal{U} = \gamma_\mu p^\mu$, and $d_s = d_\mathcal{U} + 1/2$.

We comment that in the limit of $d_\mathcal{U}$ equal to 1, the above decay width becomes zero since $A_\mathcal{U}$ has a factor $1/\Gamma(d_\mathcal{U}-1)$ which goes to zero when $d_\mathcal{U} \to 1$. Physically this is because that in this limit $A_{d_\mathcal{U}}\theta(p^2)/p^{2(2-d_\mathcal{U})} \to 2\pi\delta(p^2)$ and the unparticle behaves as a massless particle. When $p^2 = m_n^2$, the delta function forces the width to be zero.

Saturating the experimental bound on $n \to$ invisible by the above decay, one can constrain the unparticle interactions. In Fig.1, we show constraint on λ^s_{QQD} as a function of $d_\mathcal{U}$ for fixed $\Lambda_\mathcal{U} = 10$ TeV. We see that the constraint is very stringent. If $\Lambda_\mathcal{U}$ is set to be larger, the coupling becomes larger. In Fig. 2, we show the bound on the scalar $\Lambda_\mathcal{U}$ with $\lambda_i = 1$. Setting λ_{QQD} to be of order 1, the unparticle scale $\Lambda_\mathcal{U}$ would be required to be larger than 10^{10} GeV (for $d_\mathcal{U} = 1.5$, $\Lambda^s_\mathcal{U}$ is around 10^{12} GeV).

Replacing $2\lambda^s_{QQD}$ by λ^s_{UDD} and λ^s_{DDU} in eq. (4), one obtains the decay widths induced by the operators $\bar{U}^c_R D_R \bar{O}^s D_R$ and $\bar{D}^c_R D_R \bar{O}^s U_R$.

The operators in eq.(1) can induce $p \to e^+ + \pi^0, \bar{\nu} + \pi^+$ and $n \to e^+ + \pi^-, \bar{\nu} + \pi^0$ decays which have been studied. The couplings are stringently constrained. When attaching an scalar unparticle $O_\mathcal{U}$ to the operators in eq.(1), one would naturally consider $p \to e^+ + \pi^0 + O_\mathcal{U}, \bar{\nu} + \pi^+ + O_\mathcal{U}$ and $n \to e^+ + \pi^- + O_\mathcal{U}, \bar{\nu} + \pi^0 + O_\mathcal{U}$ decay modes to constrain the interactions. We find, however, that there are simpler decay modes such as $p \to e^+ + O_\mathcal{U}$, and $n \to \bar{\nu} + O_\mathcal{U}$ which can be used to constrain the interactions. Let us take $\bar{Q}^c_L Q_L \bar{L}^c_L Q_L O_\mathcal{U}$

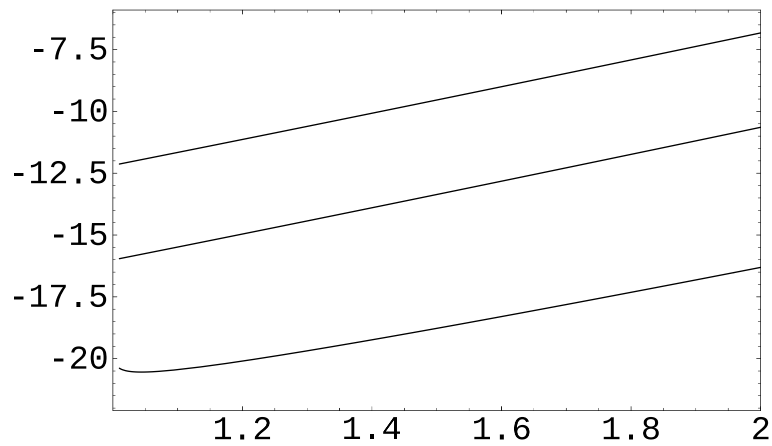

FIG. 1: Constraints on $log_{10}\lambda_i$ as functions of $d_{\mathcal{U}}$ for $\Lambda_{\mathcal{U}} = 10$ TeV and $|\alpha| = |\beta| = 0.01$ GeV^3. The curves from bottom up are the upper bounds for λ^s_{QQD}, $\lambda^{\mathcal{U}}_{QQQ}$ and λ^μ from the processes $n \to +O^s_{\mathcal{U}}$, $n \to \bar{\nu} + O_{\mathcal{U}}$, and $n \to \bar{\nu} + O^\mu_{\mathcal{U}}$, respectively.

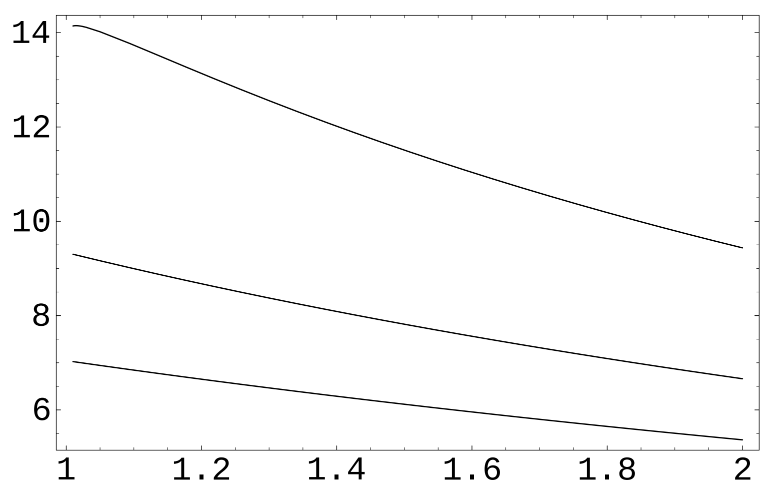

FIG. 2: Constraints on $log_{10}(\Lambda_{\mathcal{U}}/GeV)$ as functions of $d_{\mathcal{U}}$ for λ_i and $|\alpha| = |\beta| = 0.01$ GeV^3. The curves from top down are the lower bounds for $log_{10}(\Lambda_{\mathcal{U}}/GeV)$, from the processes $n \to O^s_{\mathcal{U}}$, $n \to \bar{\nu} + O_{\mathcal{U}}$, and $n \to \bar{\nu} + O^\mu_{\mathcal{U}}$, respectively.

to show the details. We have the effective Lagrangian for these decays

$$L(p \to e^+ + O_{\mathcal{U}}) = 2\frac{\lambda^{\mathcal{U}}_{QQQ}}{\Lambda^{d_{\mathcal{U}}+2}_{\mathcal{U}}}\beta \bar{e}^c_L p O_{\mathcal{U}}, \quad L(n \to \bar{\nu} + O_{\mathcal{U}}) = -2\frac{\lambda^{\mathcal{U}}_{QQQ}}{\Lambda^{d_{\mathcal{U}}+2}_{\mathcal{U}}}\beta \bar{\nu}^c_L n O_{\mathcal{U}}. \tag{5}$$

When neutrino and electron masses are neglected, the formulas for the decay width for

$p \to e^+ + O_{\mathcal{U}}$ and $n \to \bar{\nu} + O_{\mathcal{U}}$ are the same. We have

$$\Gamma = A_{d_{\mathcal{U}}} \frac{|\lambda^{\mathcal{U}}_{QQQ}|^2}{16\pi^2} \frac{|\beta|^2}{m_N \Lambda^4_{\mathcal{U}}} \left(\frac{m_N}{\Lambda_{\mathcal{U}}}\right)^{2d_{\mathcal{U}}} B(3, d_{\mathcal{U}} - 1), \tag{6}$$

where $m_N = m_p$ and $M_N = m_n$ for proton and neutron decays. $B(a, b)$ is the standard β-function.

The experimental bound on $n \to$ invisible from Kamland can be used to constrain $n \to \bar{\nu} + O_{\mathcal{U}}$ since neutrino is not measured. We show the constraint on the parameter $\lambda^{\mathcal{U}}_{QQQ}$ in Fig. 1. It can be seen that the constraint is also very strong although weaker than that for λ^s_{QQD}. Setting $\lambda^{\mathcal{U}}_{QQQ}$ to be one, with $d_{\mathcal{U}} = 1.5$, the scale $\Lambda_{\mathcal{U}}$ is required to be larger than 10^8 GeV. More details are shown in Fig. 2.

The experimental signature for the decay mode $p \to e^+ + O_{\mathcal{U}}$ is $p \to e^+ +$invisible. If one takes the bound $\tau > 6 \times 10^{29}$ years for $p \to e^+ +$ anything from PDG[2, 17] and saturate it with $p \to e^+ + O_{\mathcal{U}}$, one would obtain similar constraints as that from $n \to \bar{\nu} + O_{\mathcal{U}}$. The other operators will induce similar decays, and the constraints are also similar.

Finally let us discuss vector unparticle induced baryon number violating decays. There are many operators at dimension $7 + d_{\mathcal{U}}$ which can induce such decays. For illustration we provide details for the operator $\bar{Q}^c_L Q_L \bar{L}^c_L \sigma_{\mu\nu} Q_L \partial^\mu O^\nu_{\mathcal{U}}$. This operator will induce $p \to e^+ + O^\mu_{\mathcal{U}}$, and $n \to \bar{\nu} + O^\mu_{\mathcal{U}}$. The effective Lagrangian for these decays are given by

$$\begin{aligned} L(p \to e^+ + O_{\mathcal{U}}) &= 2\frac{\lambda^\mu_{QQQ}}{\Lambda^{d_{\mathcal{U}}+3}_{\mathcal{U}}} \beta \bar{e}^c_L \sigma_{\mu\nu} p \partial^\mu O^\nu_{\mathcal{U}}, \\ L(n \to \bar{\nu} + O_{\mathcal{U}}) &= -2\frac{\lambda^\mu_{QQQ}}{\Lambda^{d_{\mathcal{U}}+3}_{\mathcal{U}}} \beta \bar{\nu}^c_L \sigma_{\mu\nu} n \partial^\mu O^\nu_{\mathcal{U}}. \end{aligned} \tag{7}$$

Neglecting neutrino and electron masses, we obtain the decay rates for these decays

$$\Gamma = A_{d_{\mathcal{U}}} \frac{|\lambda^\mu_{QQQ}|^2}{32\pi^2} \frac{|\beta|^2}{\Lambda^6_{\mathcal{U}}} m_N \left(\frac{m_N}{\Lambda_{\mathcal{U}}}\right)^{2d_{\mathcal{U}}} \frac{6d_{\mathcal{U}} + 9}{d_{\mathcal{U}} + 2} B(3, d - 1). \tag{8}$$

Again using $n \to$ invisible data, one can constrain the couplings. We show the results in Fig.1. From the figure it is clear that the constraint is weaker compared with previous constraints, but is still very strong. Setting λ^μ_{QQQ} to be one, with $d_{\mathcal{U}} = 1.5$, the scale $\Lambda_{\mathcal{U}}$ is required to be larger than 10^6 GeV as can be seen from Fig. 2.

In summary, we have studied baryon number violating nucleon decays induced by unparticle interactions with the standard model particles. We found that the lowest dimension operators can arise at dimension $6 + (d_s - 3/2) = 6 + (d_{\mathcal{U}} - 1)$ with the unparticles being

a spinor. For scalar and vector unparticles, the lowest order operatoers arise at $6 + d_{\mathcal{U}}$ and $7 + d_{\mathcal{U}}$ dimensions, respectively. For spinor unparticle, the dominant decay mode is $n \to O^s_{\mathcal{U}}$. Experimental bound on invisible decay of a neutron from KamLAND puts very stringent bounds on the relevant coupling. If the coupling is of order one, the unparticle scale is required to be larger than 10^{10} GeV for $d_{\mathcal{U}} < 2$. For scalar and vector unparticles, the dominant decay modes are $n \to \bar{\nu} + O_{\mathcal{U}}(O^{\mu}_{\mathcal{U}})$ and $p \to e^+ + O_{\mathcal{U}}(O^{\mu}_{\mathcal{U}})$. Invisible decay of a neutron bound also puts very strong constraints on the relevant couplings and push the unparticle scales for sclar and vector to be 10^7 GeV and 10^5 GeV for $d_{\mathcal{U}} < 2$, repectively. Data on proton decay into a positron and missing energy can also put stringent constrains.

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